Hypoxia and Flight Performance of Military Instructor Pilots in a Flight Simulator

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TEMME LA, STILL DL, ACROMITE MT. *Hypoxia and flight performance of military instructor pilots in a flight simulator.* Aviat Space Environ Med. 2010; 81:7:654-9.

Introduction: Military aircrew and other operational personnel frequently perform their duties at altitudes posing a significant hypoxia risk, often with limited access to supplemental oxygen. Despite the significant risk hypoxia poses, there are few studies relating it to primary flight performance, which is the purpose of the present study. ***Methods***: Objective, quantitative measures of aircraft control were collected from 14 experienced, active duty instructor pilot volunteers as they breathed an air/nitrogen mix that provided an oxygen partial pressure equivalent to the atmosphere at 18,000 ft (5486.4 m) above mean sea level. The flight task required holding a constant airspeed, altitude, and heading at an airspeed significantly slower than the aircraft's minimum drag speed. The simulated aircraft's inherent instability at the target speed challenged the pilot to maintain constant control of the aircraft in order to minimize deviations from the assigned flight parameters. ***Results***: Each pilot's flight performance was evaluated by measuring all deviations from assigned target values. Hypoxia degraded the pilot's precision of altitude and airspeed control by 53%, a statistically significant decrease in flight performance. The effect on heading control effects was not statistically significant. There was no evidence of performance differences when breathing room air pre- and post-hypoxia. ***Discussion***: Moderate levels of hypoxia degraded the ability of military instructor pilots to perform a precision slow flight task. This is one of a small number of studies to quantify an effect of hypoxia on primary flight performance.

Keywords: hypoxia, flight performance, aviation, simulation, instrument flight, reduced oxygen breathing device, ROBD.

HYPOXIA has long been a major concern for aviation (4). It can degrade performance or even produce complete incapacitation, and the risks increase with increasing altitude. As altitude increases and barometric pressure decreases, less air is available per unit volume. Since oxygen is a constant 20.95% of air, there is, in turn, less oxygen per unit volume. While an individual's lung volume is approximately constant, the amount of inspired oxygen available with each breath decreases with increases in altitude. For example, the atmospheric pressure at sea level is about 760 mmHg, resulting in an alveolar oxygen pressure of approximately 103 mmHg. In contrast, at an altitude of about 14,000 ft (4267.2 m), the atmospheric pressure decreases to about 447 mmHg and the alveolar oxygen pressure decreases to approximately 48 mmHg (8). Meanwhile, the body's consumption of oxygen at altitude remains constant in the face of the decreased oxygen. Consequently, individuals exposed to altitude face the challenge of functioning under conditions of reduced available oxygen. As altitude increases further with additional decreases in available oxygen, the challenge becomes even greater.

The literature describes the broad, consistent impact that altitude-related hypoxic stress has on individuals. For example, one report described the use of an anonymous, self-report questionnaire to assess the prevalence of hypoxic symptoms experienced by helicopter aircrew operating at altitudes below 10,000 ft (3048 m) (12). The symptoms were grouped into five categories: 1) general effects; 2) cognitive; 3) psychomotor; 4) visual; and 5) behavioral. The general effects, reported by 64.2% of the respondents, were the most common and included light-headedness, physical tiredness, respiratory effects, tingling, mental tiredness, tachycardia, and headaches. Cognitive effects, reported by 56.6% of the respondents, described an impact on judgment, memory, confusion, and the ability to calculate. Psychomotor effects, reported by 45.3% of the respondents, described an impact on reaction time, dexterity, and the ability to communicate. Vision effects, reported by 7.5% of the respondents, described an impact on peripheral vision, acuity, and perceived light intensity. Behavioral effects, reported by 7.5% of the respondents, identified an impact on mood and personality. Similar symptoms were reported in F/A-18 aviators undergoing hypoxia refresher training using instrumentation similar to that used in the present study (1).

Current experience provides ample basis to expect that moderate levels of hypoxia will interfere with a pilot's ability to control an aircraft. There is, however, surprisingly little direct evidence to support this. Almost all of the evidence for the impact of hypoxic stress on a pilot's performance is indirect, extrapolated from cognitive and other performance testing designed to assess those skills considered important for a pilot's ability to control an aircraft. Typical cognitive skills assessed include vigilance, psychomotor performance, perceptual speed, visual tracking, mental rotation, color vision, memory, and so forth (2,3,9).

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This manuscript was received for review in October 2009. It was accepted for publication in April 2010.

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DOI: 10.3357/ASEM.2690.2010

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Hypoxia And Flight Performance Of Military Instructor Pilots In A Flight Simulator**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Aeromedical Research Laboratory,P.O. Box 620577,Fort Rucker,AL,36362**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Aviation Space Environtal Medicine 2010 Jul;81(7)

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Gold and Kulak noted that although a number of studies reported that hypoxic stress affected psychomotor performance, the studies failed to show any flight performance deficit in actual aircraft or flight simulators (5). Their study using a LinkGAT-1 instrument trainer may have been the first controlled laboratory study to report a measured deficit in pilot performance due to hypoxia. In their study, pilots flew an instrument landing system (ILS) approach as the pilots breathed a mix of oxygen and nitrogen to simulate air at 12,000 and 15,000 ft (3657.6 and 4572 m) above mean sea level (MSL). This study identified increased deviation errors in altitude, heading, airspeed, vertical velocity, and glide slope, with higher altitudes producing a greater error. A subsequent report assessed both flight performance accuracy and the occurrence of procedural errors during cross-country flights in a general aviation simulator while oxygen-nitrogen mixes simulated an altitude up to 12,500 ft (3810 m) MSL (7). The results showed a significant increase in procedural errors due to hypoxia, but no convincing evidence for any impact on primary flight performance, i.e., the pilot's stick and rudder control of the aircraft. Most recently, a presentation reported a decrease in simulated flight performance that correlated with a decrease in cognitive performance at a simulated altitude of 15,000 ft (4572 m) MSL, but this study has yet to be published (10). In summary, despite the reasonable expectation that primary flight performance degrades in the face of hypoxic stress, the evidence for such a hypoxic effect on flight performance is surprisingly thin and the situation noted more than 35 yr ago by Gold and Kulak has not substantially changed. The results of the present study add to this literature and suggest that hypoxic stress degrades the primary flight performance of military instructor pilots using a commercially available, off-the-shelf flight simulator.

METHODS

Subjects

Active duty military instructor pilots volunteered for this study. They had an average age of 32 yr (SD = 3), and an average of 2235 (SD = 737) flight hours experience. All volunteers were on active flight status at the time of the study. Data collection for this study was reviewed and approved by the Institutional Review Board of the Naval Aerospace Medical Research Laboratory and the Navy Bureau of Medicine and Surgery. Data analysis and reporting were reviewed and approved by the Institutional Review Board of the U.S. Army Aeromedical Research Laboratory.

Instrumentation

All flight data were collected using a desktop flight simulator consisting of an aerodynamic simulation model of a Cessna 172 (Elite 4 Propeller Version 4, with data export capability) and flight controls consisting of a control yoke, throttle quadrant, and rudder pedals (Precision Flight Control, Jack Birch Edition). The simulator software ran on a Macintosh computer to provide the aerodynamic model, and a 19-in flat panel (1024 × 780 pixels, approximately 15 cd · m^{-2}) rendering of the Cessna's conventional flight instruments. The small "out of the window" view was obscured. The manufacturer modified this simulator to export flight data, which were recorded on a PC at 60 Hz (15).

Hypoxic stress was induced using an early prototype of the commercially available Reduced Oxygen Breathing Device (ROBD) (11). In general, the ROBD dilutes breathable air with nitrogen, an inert gas, to reduce the available oxygen so that it is equal to that found at defined altitudes. For the present study, the defined altitude was 18,000 ft (5486.4 m) MSL. It should be noted that the prototype used for the present study differed from the currently available commercial ROBD in that the gas mixing circuit of the prototype was open to the room and the nitrogen was mixed with the ambient room air rather than bottled or compressed air as is the usual procedure with the commercial ROBD. Since the circuit was open to room air, the pressure of the ROBD's mixed air/nitrogen gas output was the room's atmospheric pressure, so that the ROBD did not impose any differential changes in respiratory resistance over the different experimental conditions.

Flight Task

Pilots controlled the Cessna 172 simulation to maintain a constant heading of 180°, a constant altitude of 3000 ft (914.4 m) MSL, and a constant airspeed of 70 knots (kn). It is important to note that the 70-kn airspeed is below the aircraft's minimum drag speed of 85 kn, which means that the aircraft simulation was operated in a range at which it is unstable, making the flight task challenging. Specifically, this slow flight task not only requires aircraft performance to be continually monitored and controlled, the task reverses the normal relation between speed and drag. To clarify, while flying above the minimum drag speed, slowing down by raising the nose with the elevator reduces drag, freeing engine energy for climb. In contrast, while flying below minimum drag speed, slowing down by raising the nose with the elevator increases drag, slowing the aircraft even more. The practical result is that when flying faster than minimum drag speed, altitude corrections can be accomplished with elevator input alone, but when flying slower than minimum drag speed, as is the case in this study, altitude corrections require power adjustments and the elevator is used to control speed, not altitude. Power changes in aircraft of the type used in this study require coordinated rudder input to prevent yaw and maintain a stable heading. If the rudder is not coordinated with the power changes, then the resulting yaw-induced roll will require an aileron input for correction. Thus, active control of all four flight controls (throttle, elevator, rudder, and aileron) is required to maintain flight at the assigned altitude, heading, and air speed. As an aside, it may be noted that this airspeed range (slower than minimum drag speed) is typical for landing approaches and that landing approach accidents, while

uncommon for professional aviators, show up frequently in accident reports of recreational pilots, suggesting that this flight task may have important operational implications for civilian aviation independent of hypoxia.

Unaccelerated flight slower than minimum drag speed has several characteristics that make it a useful tool for research. The task can be continued for an indefinite period of time, yet the difficulty remains constant throughout. Since performance over the course of the whole maneuver is equally difficult, performance can be directly compared among segments of the maneuver, which simplifies the analysis and interpretation of results. In addition, the task produces a measure of performance that is continuous, has equal intervals, and a defined zero so that it meets the definition of a ratio scale, and so supports all statistical analysis manipulations (6,13).

Design

The strategy was to record the heading, altitude, and air speed hold capability of pilots as they controlled a flight simulator through a maneuver that provided precisely defined, constant target values for the duration of the maneuver. Although the flight task and the required performance of the pilot were constant, there were three epochs to the flight. During Epoch A, pilots breathed ambient room air (approximately 20 feet MSL). During Epoch B, pilots breathed ambient air diluted with nitrogen such that the air/nitrogen mix produced an oxygen partial pressure typically encountered at 18,000 ft MSL. During Epoch C, pilots again breathed ambient room air. Thus, the independent variable was flight epoch, of which there were three levels: prehypoxic, hypoxic, and posthypoxic.

All subjects were exposed to all three epochs and the three dependent measures of altitude, heading, and air speed were recorded for all subjects. The data were analyzed using a standard within-subjects multivariate statistical analysis procedure, sometimes referred to as a doubly-multivariate analysis of variance. The analysis evaluated the hypothesis that performance would be more variable during Epoch B than during either Epoch A or Epoch C. All statistical analyses were performed with SPSS 17.

Procedures

Testing for each subject was completed in one day. Each volunteer reported to the laboratory around 0900 with their medical records. The informed consent process was conducted first, followed by a medical check by the physician identified in the research protocol as responsible for ensuring that the volunteers were medically qualified to be on flight status. These two procedures required about 1 h. After the physician confirmed that the volunteers met the medical criteria, the volunteers received 2 h of familiarization and training, including a discussion of the theory and function of the ROBD, safety procedures, flight hardware, and flight task. During this training, the volunteers familiarized themselves with the flight simulation aircraft, the slow flight task, and became comfortable breathing room air with the respirator, its mounting hardware, and an ear-mounted pulse oximetry sensor to measure blood oxygen saturation. The respirators were fit-tested to assure appropriate seal and function for each volunteer. All the volunteers were already well-acquainted with the standard military aviation respirators used in this study. Furthermore, they were all familiar with the challenges that slow flight posed. The volunteers were released at 1200 for lunch and asked to return at 1300 to begin the hypoxia data collection process. The afternoon data collection session began following final adjustments to the respirator and oxygen sensor fit and a 5-min test flight that ensured that all the instrumentation was in order and the volunteer was comfortable with the task.

The experiment started with the volunteer taking control of the simulator at the designated performance targets of 180° heading, 3000 ft (914.4) MSL altitude, and 70 kn indicated air speed (IAS). When the volunteer was satisfied that the simulator was functioning and adequately under control, the volunteer signaled that data collection may begin. As far as the volunteer was concerned, the task was constant, to keep the simulator as close to these performance targets for the total duration of the 26-min flight. While the volunteer breathed through the respirator for the entire flight, the source of the air was changed at specific times. For the first 5 min of the flight, the volunteer breathed room air; from minutes 5 through 18, the ROBD provided the air/nitrogen mix with the oxygen partial pressure equivalent of 18,000 ft; and from minutes 18 through 26, the volunteer again breathed room air. The flight task target altitude remained at 3000 ft during the entire 26 min. During the total flight, pulse oximetry monitored a volunteer's arteriole blood oxygen saturation and an emergency medical technician monitored the volunteer's physical appearance, breathing, and condition. Subjects were instructed to breathe normally, were monitored for compliance, and were reminded as needed by the researchers and the attending emergency medical technician. During the hypoxic stress, the blood oxygen percent saturation was not permitted to fall below 60%, as per the procedures and criteria described by Sausen et al. (11).

Following completion of the flight, the volunteer remained in the laboratory for observation for at least 30 min. During this time, the volunteer was engaged in a discussion of the experiment. The discussion addressed any additional questions and comments of the volunteer.

RESULTS

Sample data from one volunteer is illustrated in **Fig. 1**. The bottom panel shows a systematic drift in heading over the course of the flight from about 180° to about 185°. This drift was an intended feature that the flight simulation incorporated to emulate gyroscopic drift.

Performance scores were calculated from these data over three 5-min epochs of the flight (horizontal lines

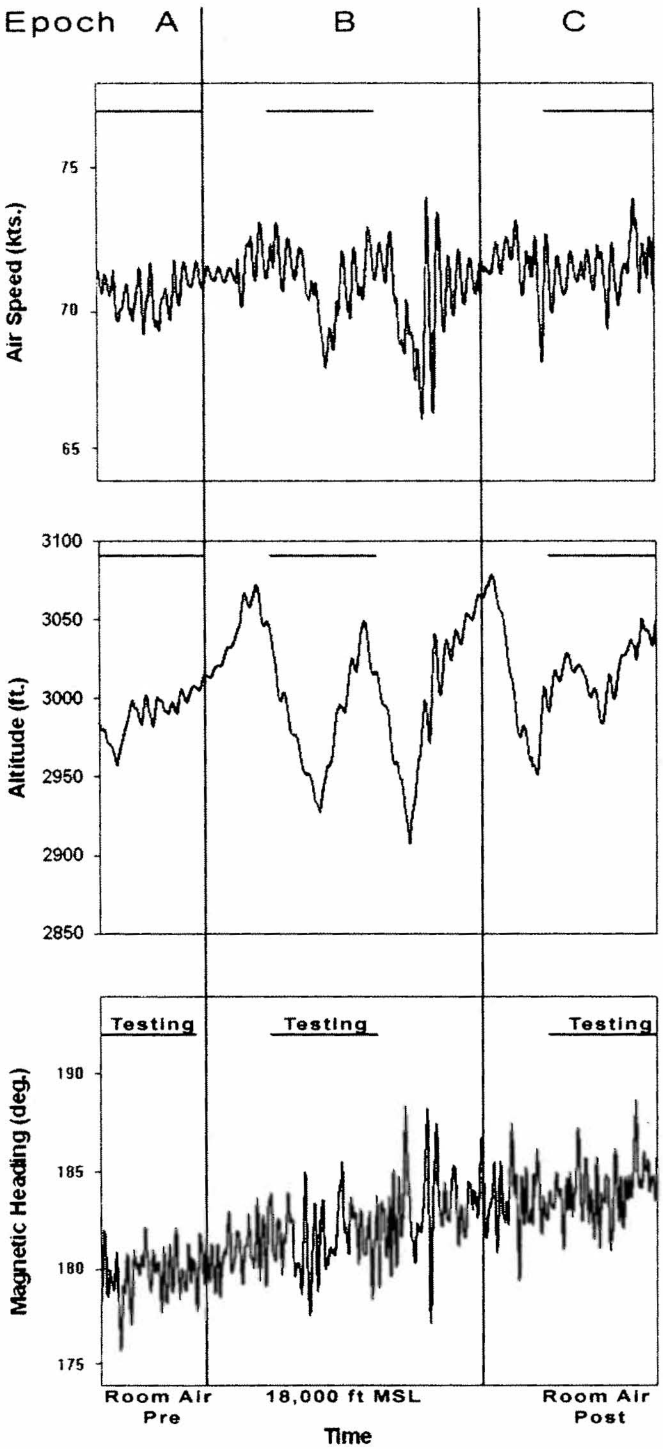

Fig. 1. Sample raw flight performance data recorded from one subject. Flight performance is plotted against time for the duration of the flight. The top, middle, and bottom panels are airspeed (in knots), altitude (in feet), and heading (in degrees), respectively. The three panels have the common abscissa, flight time in minutes. Time 0 is the start of flight data collection; the vertical bars at 5 min and 18 min mark the start and stop of the 18,000-ft hypoxic exposure. The two vertical bars divide the flight into the three phases. The horizontal line segments shown in each phase provide a 5-min scale and the epoch for which performance was scored.

in Fig. 1). The performance scores are the standard deviations calculated separately for altitude, heading, and air speed over each of the three 5-min epochs. Thus, the performance score is a measure of variability so that the larger the performance score, the poorer is the performance. Epoch A covers the interval from the start of flight data collection to the moment when hypoxic stress was introduced, indicated by the first vertical bar. Epoch B covers the 5-min interval from minute 8 to 13. Note that Epoch B began 3 min after the switch to the hypoxic stress. This 3-min delay between the introduction of the hypoxic stress and the start of Epoch B reduced the impact of transients on the performance scores by providing time for physiology and behavior to stabilize. Epoch C covers the 5-min interval from minutes 21 to 26. Note that Epoch C began 3 min after the switch from the hypoxic stress to room air. This 3-min delay between the introduction of room air and the start of Epoch C reduced the impact of transients on the performance scores by providing time for physiology and behavior to stabilize. Such performance scores were generated for each subject individually. The top, middle, and bottom panels of **Fig. 2** show for Epochs A, B, and C the average (mean ± SEM) performance score for air speed, altitude, and heading, respectively, for the group of 14 subjects.

The multiple analysis of variance (MANOVA) tests showed that statistically significant differences ($P <$ 0.035) occurred among the three dependent variables over the three epochs, a finding that justified further univariate analyses.

Since Mauchly's tests indicated that the air speed measurement violated the assumption of sphericity (χ^2 (2) = 7.917, $P < 0.019$), the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ϵ = 0.674) for the ANOVA. This ANOVA showed that there was a statistically significant difference ($P < 0.032$) in air speed performance among the three epochs [F (1.349, 17.532) = 4.878]. Since a matched-pair t-test showed no statistically significant difference in air speed performance between Epoch A (M = 1.69 kn, SE = 0.33 kn) and Epoch C (M = 1.82 kn, SE = 0.33 kn) [t(13) = -0.652, $P < 0.526$, r = 0.83], the air speed performance recorded during these epochs was arithmetically averaged for each subject. The resulting average air speed performance for sea-level was compared with air speed performance during Epoch B, the period of hypoxia, using a matched-paired t-test. The comparison showed that the performance during Epoch B (M = 2.69 kn, SE = 0.63 kn) was significantly more variable that the mean of Epoch A and C (M = 1.75 kn, SE = 0.32 kn) [t(13) = 2.389, $P < 0.033$, r = 0.866].

Since Mauchly's tests indicated that the altitude measurement did not violate the assumption of sphericity (χ^2 (2) = 4.773, $P < 0.092$), the degrees of freedom were not corrected for the ANOVA. This ANOVA showed that there was a statistically significant difference ($P < 0.002$) in altitude performance among the three epochs [F (2, 26) = 7.648]. Since a matched-pair t-test showed no statistically significant difference in altitude performance between Epoch A (M = 22.54 ft, SE = 3.13 ft) and Epoch C (M = 22.69 ft, SE = 2.88 ft) [t(13) = −0.052, $P < 0.960$, r = 0.646], the altitude performance recorded during these two epochs was arithmetically averaged for each

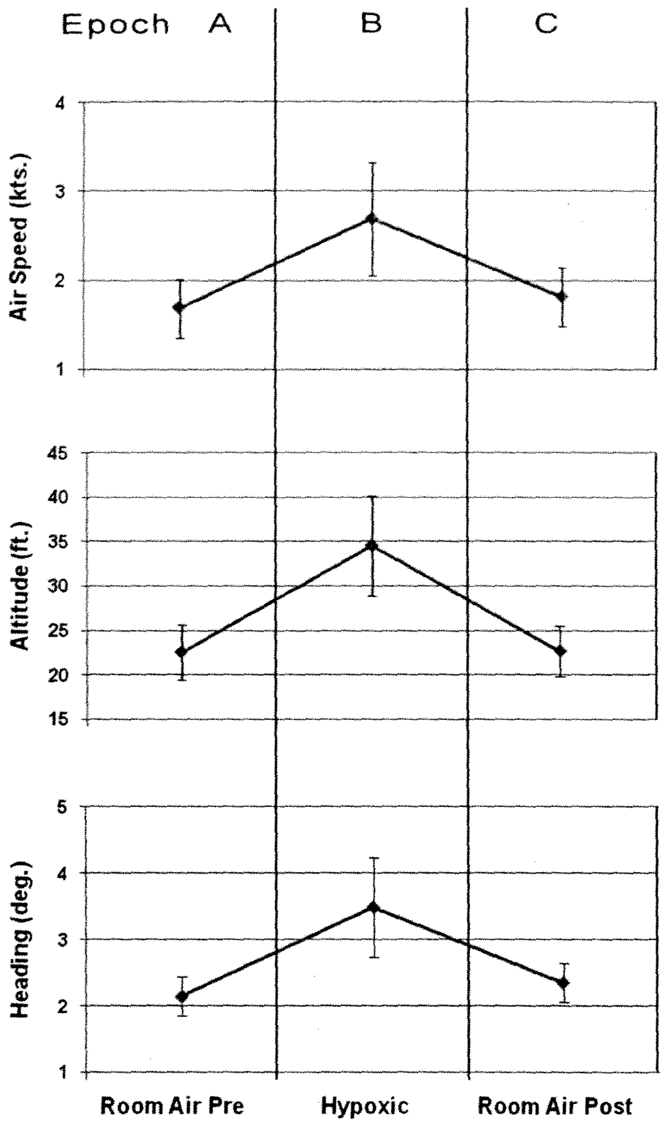

Fig. 2. Mean (± SEM) flight performance score averaged over all volunteers for indicated air speed, altitude, and heading in the upper, middle and lower panels, respectively. Performance is scored as the standard deviation (SD) calculated over each 5-min epoch for each subject. Epoch A = Room Air Pre; Epoch B = 18,000 ft MSL; Epoch C = Room Air Post.

subject. The resulting average altitude performance for sea-level was compared with altitude performance during Epoch B, the period of hypoxia, using a matched-paired *t*-test. The comparison showed that the performance of pilots during Epoch B (M = 34.58 ft, SE = 5.65 ft) was significantly more variable than the mean of Epochs A and C (M = 22.60 ft, SE = 2.73 ft) [$t(13) = 3.211$, $P < 0.007$, r = 0.826].

Since Mauchly's tests indicated that the heading measurement violated the assumption of sphericity (χ^2 (2) = 36.244, $P < 0.0001$), the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity (ε = 0.513). With these corrections, the ANOVA failed to show a statistically significant difference among the three epochs [F (1.025, 13.325) = 4.060, ($P < 0.064$)]. No additional statistical analysis was therefore conducted.

DISCUSSION

The results of the present study convincingly demonstrate that the experimental procedures degraded the precision with which pilots are able to execute the slow flight task. The analysis showed that there were no statistically significant differences in the flight performance between Epochs A and C, which are the two epochs during which the pilots were breathing room air, but during Epoch B, which is the interval over which pilots were exposed to the oxygen partial pressure equivalent to that of 18,000 ft MSL, flight performance was more variable than during the mean of Epochs A and C. Specifically, the SD of air speed was about 0.94 kn more during Epoch B than during Epochs A and C. Similarly, the SD of altitude was about 12 ft more during Epoch B than during Epochs A and C. These differences in air speed and altitude SD were statistically significant. It should be pointed out that the SD of heading was about 1.24° more during Epoch B than during Epochs A and C, a difference that was not statistically significant.

It might be argued that flight performance should be degraded considering the magnitude of the stress, 18,000 ft MSL. In fact, one might be tempted to argue that the results could be called into question if a performance deficit were not found, but this would overlook the fact, mentioned earlier, that the present results are among the very few reports that do demonstrate a deficit in pilot flight performance directly traceable to hypoxia. Almost the whole set of literature describing the effects of hypoxia on pilot performance is based on extrapolations to aviation from the performance on psychometric tasks that are argued to be important for pilot performance in an aircraft. In this regard, the major observation may be that the measured deficit in pilot performance seems relatively modest; the hypoxic stress certainly did not incapacitate the pilots. This would seem to imply that the pilots were relatively resilient to the effects of hypoxia. Possibly the most telling aspect of the study is the small impact on performance that relatively severe hypoxia may have when the exposure is less than 8 min.

The experiment was designed around a flight task with specific characteristics. The task, slow flight, is a continuous, constant maneuver of uniform difficulty that can be continued for any arbitrary duration, which means that performance at any time of the task should be directly comparable to performance at any other time. The experimental procedures were refined to reduce the amount of uncontrolled variability in order for the experiment to be sensitive enough to uncover small systematic differences in performance. The success of the procedures in reducing uncontrolled experimental error may be one of the reasons that this study is among the few to report an effect of hypoxia on flight performance. In fact, some might argue that the study demonstrated statistically significant effects only because the experimental noise has been controlled sufficiently to uncover what for all practical purposes are inconsequentially small performance deficits. Clearly, the present study cannot resolve such a criticism, which requires a bridge

between the laboratory/simulation and the real world. There is, however, another way of considering the magnitude of these results. Statistics provide a standardized metric for assessing the size on an effect. Using this statistical metric, the effect size of hypoxia on air speed and altitude accounts for about 75% (r = 0.866) and 68% (r = 0.826) of the observed variance, respectively. By convention, such effect sizes are generally considered large. Another way of considering the magnitude of the effect is to note that the SD for air speed and for altitude during Epoch B is about 1.5 times that measured during Epochs A and C. From this point of view, the effect of the hypoxic exposure is rather marked.

For the present study, the subjects were rendered hypoxic by breathing through a standard aviator's oxygen mask with a mixed air/nitrogen simulation of the air encountered at 18,000 ft MSL. During these exposures, pulse oximetry was routinely monitored to ensure that the percent blood oxygen did not fall below 60%. This means that the ROBD was set to produce a constant output, but aside from the blood oxygen saturation percent, the subject's physiological response to this constant stimulus condition was not monitored. We have recently demonstrated a large between-subject range in blood oxygen saturation percent while exposed to constant ROBD simulated altitudes (14). This creates the potential for uncontrolled physiological variability to affect the results of the present study. Despite this possible source of uncontrolled experimental variability, the present study had sufficient power to uncover a precisely measurable deficit in performance directly attributable to hypoxia, and in the process the study demonstrated a practicable set of experimental methodologies and procedures. To this extent, the present work describes a system that can be used to assess the effectiveness of interventions and countermeasures. For example, the degradation in precision flight could be due to the effect hypoxia has on aspects of cognitive function, motor control, sensory function, or some combination of these. The challenge would be to tease these apart and clarify their relative importance for the flight task. Such information, which would sharpen our understanding of the effects of hypoxia, could guide the design of interventions and countermeasures tailored to address the specific psychophysiological sources of the deficit.

All the volunteers expressed the opinion that the experience of flying a simulator under controlled hypoxic exposures was an extremely worthwhile training event and far more useful than the hypoxia training in which they previously participated—training that involved going to a much higher altitude and demonstrating the rapid loss of eye/hand coordination in tasks that have no direct relevance to flying. This speaks to the reasonableness of the continued use of the ROBD and the flight simulator as a component of the hypoxia training for aviators, as is currently being implemented by the U.S. Army School of Aviation Medicine and the U.S. Naval Survival Training Institute.

ACKNOWLEDGMENTS

The authors are grateful to the Naval Aerospace Medical Research Laboratory (NAMRL) for supporting this research through the Annual Navy Medical In-House Laboratory Independent Research (ILIR) Program (FY02-03) under the project: "Flight Performance With A Human-Centered Computing Cockpit Display System, OZ, Under Hypoxic Conditions."

The opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Army and/or the Department of Defense.

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